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REFLECTION OF GAMMA RADIATION BY A SINGLE CRYSTAL OF COPPER

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REFLECTION OF GAMMA RADIATION BY A SINGLE CRYSTAL OF COPPER

by

Francis Marion Holmes

A Thesis Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
MASTER OF SCIENCE

Major Subject: Nuclear Engineering

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I. INTRODUCTION

The use of nuclear power is of considerable interest to those concerned with aircraft development because it could provide a means of giving aircraft greatly extended range. To be able to base military aircraft in the United States and still have a striking force anywhere in the world would be of tremendous strategic importance. Its application to long range anti-submarine and early warning operations is evident. The elimination of foreign bases alone would result in large savings to the taxpayer. Commercial aircraft applications seem rather remote at this time but should not be discounted.

The problems associated with nuclear power for aircraft are extensive; some are minor in nature, others appear almost insurmountable. In the latter category is the shielding of personnel and equipment from the radiation associated with nuclear fission. The nuclear reactor and its surrounding shield give rise to almost every known type of nuclear radiation. The gamma radiation, in particular, is difficult to absorb or attenuate. The usual approach to the problem is to use a material composed of heavy elements which absorb or attenuate the gamma-rays. Lead, steel, and concrete are commonly used for this purpose, but their comparatively low strength to weight ratio make them undesirable as structural materials in aircraft. Steel may be used in some applications. The shielding necessary results in a mass which not only contributes little to the aircraft structure but also results in concentrated stresses in the structure itself.

In some applications a high degree of gamma-ray absorption may not

be necessary. It may be completely satisfactory to accept absorption to a lesser degree and seek some method of deflection or reflection of the radiation to protect certain areas such as crew compartments or components which may be susceptible to radiation damage. An effective means of doing this could logically result in an overall saving in the mass of shielding material required.

Except for the energies usually involved, the reflection of gamma-rays may be considered similar to reflection of x-rays which has been used in commercial and scientific applications for many years. The phenomenon is not dependent on surface characteristics as in the case of light rays but rather depends on the lattice structure of the reflecting material. The optimum condition is one where the most densely packed atomic planes of a single crystal are aligned at the critical angle corresponding to the radiation energy.

It is the purpose of this investigation to determine attenuation effects associated with reflection of gamma-rays by a single metallic crystal. If the results are significant, development in the technology for construction of reflective type gamma-radiation shields may be indicated.

II. REVIEW OF LITERATURE

A large volume of literature is available on the subject of the interaction of gamma-rays with matter. Of the material available, the presentation by Goldstein (5) appears to be as complete as any. His work includes effects of higher order as well as the primary contributions of photoelectric effect, pair production, and Compton effect. Davisson and Evans (3) have presented data to predict the characteristics of photons of various energies when scattered by many of the common materials.

There is also a wealth of information on the reflection and diffraction of x-rays, a small portion of which is directly applicable. In 1914, Bragg and Bragg (1) saw, in previous work on x-ray diffraction, the implication that an x-ray beam could be reflected from the cleavage plane of a crystal and developed the equation;

$$n \lambda = 2d \sin \theta$$

where n is an integer, the order of the reflection; λ is the wavelength of the incident x-ray; d is the distance between the crystalline planes; and θ is the critical angle. The accurate measurement of lattice spacings in crystals followed since it was possible to determine the wavelengths of x-rays by the use of ruled gratings. The principles developed by Bragg and Bragg are interwoven in modern theories of solids and crystallography.

The applicability of x-ray data to gamma-ray reflection study

appears to require no special considerations. Although they differ in origin, x-rays and gamma-rays have no other properties that are different. Despite the close correlation, little information is available on the reflection of gamma-rays. Of course, the extremely small angles involved in the Bragg equation for the usual range of gamma-ray energies makes the use of gamma radiation inferior to x-rays in many applications.

In 1956 Crocker (2) conducted a study of gamma-ray reflection by small curved banks of laminated aluminum foil. Although the distances between the aluminum layers were large compared to the distances between crystal planes, he observed reflection tendencies. This method of approach was pursued in 1957 by Mergl (7). He used single crystals of zinc which had been bent in an arc. Although the crystals were stressed and the crystalline planes distorted by bending, his experimental data indicated that there was a measurable amount of gamma radiation deflected by the single crystal. In 1958 Wilson (9) compared the effectiveness of single crystals of zinc as a function of thickness and surfaces. His results again showed small amounts of reflection. He concluded that there was no measurable surface effect and the effectiveness of several crystals was essentially the same as that of one large crystal of the same size. Sasscer (8) continued the investigation in 1959 when he sought to present his results in the form of a plot of the Klein-Nishina cross section as a function of scattering angle for single crystal and polycrystalline zinc. He reasoned that any effects of reflection should appear as a variation in the Klein-Nishina cross section for the single crystal. Unfortunately, difficulties

with the counting equipment and a subsequent change in scalers resulted in poor correlation of the data before and after the change. Sasscer experienced difficulty in comparing the results obtained from the polycrystalline material with the theoretical curve. It appears that these difficulties were largely due to geometry factors associated with the source, target, and radiation measuring equipment.

On the basis of the results reviewed in the literature, the reflection of gamma-rays in measurable amounts by single crystals of metal appears feasible. While the measurement of the reflected radiation directly would be difficult, an indication of the effectiveness of a single crystal as a shielding material could be obtained by a comparison of its attenuation or scattering characteristics with those of the same material in the polycrystalline form.

III. ANALYSIS

The primary processes in the interaction of gamma-rays with matter are (a) photoelectric effect, (b) pair production, and (c) Compton effect. In the photoelectric effect, all of the energy of the incident photon is transferred to a bound electron which is ejected from the atom. In pair production, all of the energy of the incident photon is transformed into creating an electron-positron pair. Compton effect involves scattering of photons by free electrons. After striking an electron, the photon moves off at an angle with its original direction and with less energy than it had initially. The relative magnitudes of the three processes depend on the energy of the incident gamma-radiation as well as the nature of the absorbing material.

The source of gamma-radiation available for the study of single crystal characteristics was Cobalt-60 which emits primary gamma-rays of 1.3316 and 1.1715 Mev. For a comparison of the magnitude of the three material interaction effects, this may be considered as a monoenergetic source of 1.252 Mev without appreciable error.

The selection of a target material was not limited as many metals may be grown as single crystals. From practical considerations, however, the material should be available in a single crystal and in the usual polycrystalline form for comparison. If Bragg reflection occurs, then small intercrystalline plane separation would be desirable to obtain as large a critical angle as possible. The existence of closely packed planes within the crystal should be an aid in producing reflection. In consideration of the above requirements copper was selected as the

target material to be used.

With Cobalt-60 as the gamma-ray source and copper as the target material, the absorption coefficients are approximately as follows (3, p. 96): photoelectric effect, 0.0422×10^{-24} $cm^2/atom$; pair production, 0.0079×10^{-24} $cm^2/atom$; and Compton effect, 5.503×10^{-24} $cm^2/atom$. Thus, it may be seen that the Compton effect accounts for about ninety-nine percent of the interaction. In view of this, any variation in the Compton scattering exhibited by the single crystal may be considered as a significant characteristic.

Davisson and Evans (3) have presented an extensive review of the theoretical calculation of the Klein-Nishina cross section. The fraction of gamma-ray energy scattered in a given direction may be obtained by a quantum mechanical treatment of the Dirac equation for the electron,

$$I = \frac{I_o e^4}{2m^2c^4r^2} \times \frac{1 + \cos^2 \phi}{[1 + \alpha(1 - \cos \phi)]^3} \times 1 + \frac{\alpha^2(1 - \cos \phi)^2}{(1 + \cos^2 \phi)[1 + \alpha(1 - \cos \phi)]}$$

I_o = intensity of the incident beam of gamma-rays.

I = intensity of the scattered beam at the angle ϕ and distance r from the scattering electron of charge e and mass m.

$\alpha = h\nu/mc^2$.

The equation may also be written,

$$I = \frac{I_o}{r^2} \frac{h\nu'}{h\nu} k(\phi)$$

where $h\nu$ is the energy of the incident photon, $h\nu'$ is the energy of the scattered photon, and $k(\phi)$ is the cross section for the number of photons scattered per electron per unit solid angle in the direction ϕ and is known as the Klein-Nishina cross section. From the foregoing, the

quantity $k(\phi)$ is seen to be $k(\phi) = I\, h\nu\, r^2/I_o h\nu'$.

If I is equal to $B\, h\nu$, $k(\phi)$ reduces to $k(\phi) = (B/B_o)r^2$; where B_o is the incident flux, and B is the scattered flux a distance r from the scattering electron.

Experimentally, a calculation of the incident flux from the source strength and geometry factors involved plus measurement of the distance r and the scattered flux would yield a determination of $k(\phi)$. There are, however, many difficulties involved in the measurement and calculation of the above quantities. The exact measurement of distances and collimator openings is questionable except in the more precise experimental equipment. Although the source may be considered monoenergetic and of known strength, the accompanying "trash" or low energy radiation of x-rays, Compton gamma-rays, and bremstrahlung from the collimator and the source container may comprise a sizeable fraction of the total radiation. The self-absorption of the target which accounts for those photons initially scattered in the direction of the detector and reabsorbed or rescattered by the target material out of the solid angle subtended by the detector may be substantial in a thick target. Similarly, an accounting for buildup or the scattering into the detector of those photons that were initially scattered would have to be made. A simpler method of comparing the scattering characteristics of a single crystal with those of the same material in its polycrystalline form was indicated. This could be done by selecting two targets of the same dimensions. No particular difficulty was envisioned in selecting the single crystal and machining the other target to its exact specifications.

Geometry factors could be eliminated in the comparison if the geometry were kept constant. The result would be a scattering comparison based solely on measured radiation values.

Consideration was given to the reflection-scattering of gamma-rays by a single crystal. If reflection occurs when a photon enters a crystal, the photon may be scattered or it may be reflected. These processes may occur singly or in multiples or in single or multiple combinations as the photon traverses the crystal. At best, its direction and energy, if it leaves the crystal, is seen as some complicated function of the incident photon energy, the crystal material, the incident angle and the scattering angle. The analysis of such a function was beyond the scope of this investigation. The means was available, however, to investigate two of the variables experimentally, viz., incident angle and scattering angle. The best method of procedure appeared to be one of comparing the scattered radiation of the two materials for a particular incident angle over a range of scattering angles. Time permitting, this method could be repeated for a series of incident angles and thereby gain insight into the reflection-scattering dependence on the two variables.

IV. MATERIALS AND APPARATUS

A plan view of the apparatus used in this investigation is presented in Figure 1. Figures 2, 3, and 4 show the irradiation facility, target materials, target platforms, and general arrangement of the experimental equipment. A detailed description of each component follows.

A. Source

The source used was approximately two curies of Cobalt-60 which was housed in a facility built for this purpose in the Chemistry Engineering West building on the Iowa State University campus. The irradiation facility is a design described by Mc Dermott (6). Essentially it provides a source container in the form of an upright lead cylinder 16-in. in diameter and 19-in. long mounted on a concrete foundation. There are six equally spaced radiation ports, 1/4-in. in diameter and 2 1/4-in. above the table which surrounds the cylinder. The source is pinned on the end of a rack, the other end of which protrudes from an opening in the top of the cylinder. By a suitable arrangement of an electric motor and reduction gears, the source can be raised from its "safe" position within the cylinder to a position where the radiation emits from the six ports simultaneously. Up and down travel of the source is limited by two micro-switches; one stops the source in the down position, the other stops the travel in the up or radiation position. Another micro-switch operates a red light which is on at all times that the source is not in the "safe" position. Beam attenuation is provided

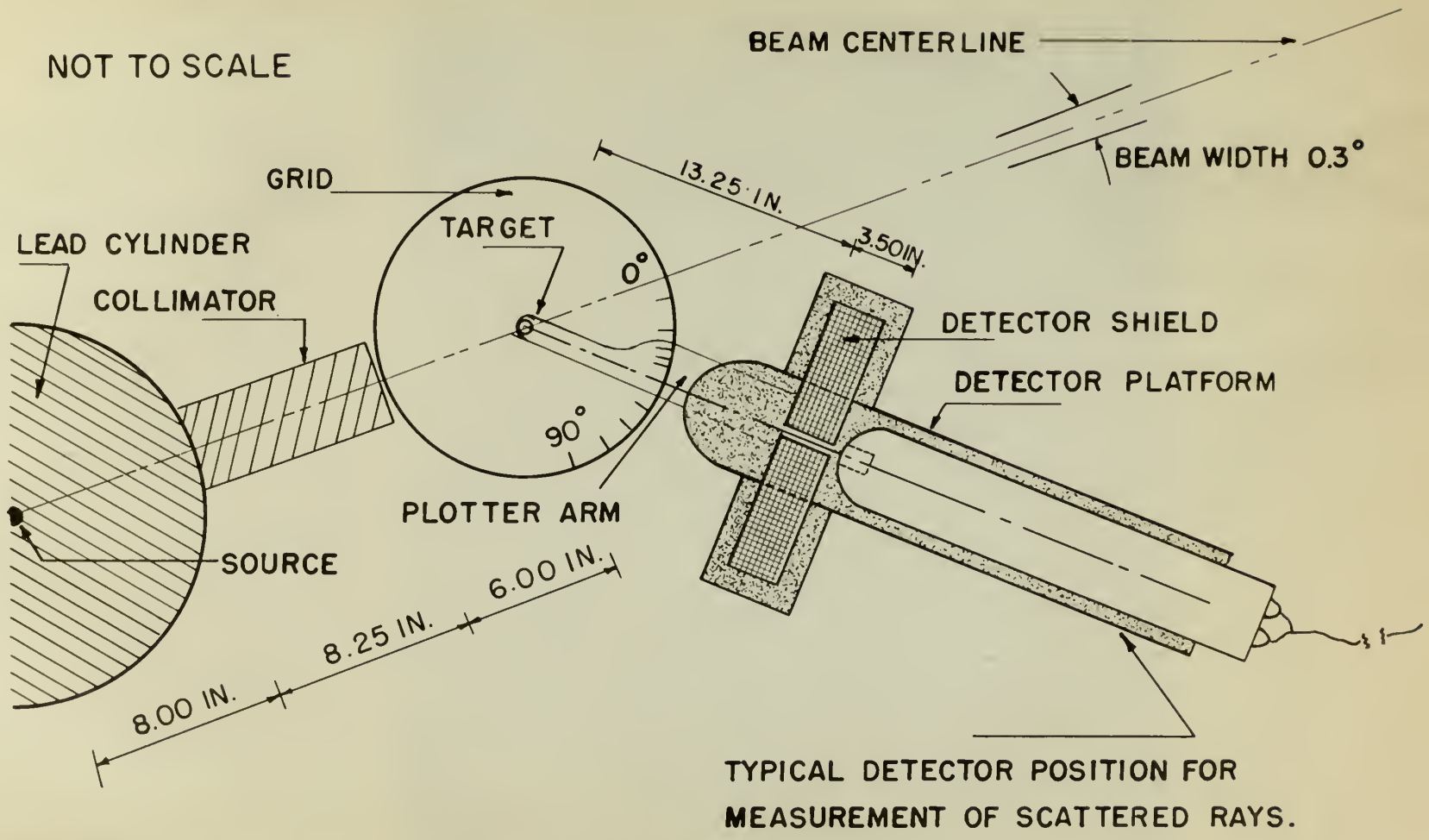

Figure 1. Plan view, experimental apparatus

Figure 2. Experimental arrangement of source, collimator, detector and scaler. Detector shielding and part of source shielding removed

Figure 3. Experimental arrangement of equipment used to find position of single crystal for gamma-ray reflection

RADIATION
HAZARD

Figure 4. Experimental arrangement of equipment used to obtain data on scattered radiation

for all ports by 5-in. thick lead slabs at the perimeter of the table.

This investigation was the first to be undertaken using the irradiation facility. Considerable time was spent checking its operation and getting it to working smoothly before the source was inserted. The source was placed in the facility and the dose rate in the working area checked by the Health Physics Group from the Ames Laboratory. Within the limits of source travel in the cylinder, the dose rate outside the table perimeter was less than 0.2 mr per hour. The maximum dose rate, all configurations, was 3.8 r per hour directly in front of one of the radiation ports. Since only one of the ports was to be used in this investigation, the others were covered with lead bricks as shown in Figure 3. This arrangement reduced the dose rate to less than 4 mr per hour at one foot from the covered ports. With the source in the irradiation position, the dose rate on top of the cylinder was approximately 20 mr per hour in the vicinity of the protruding rack. Since there would be no necessity for exposure in this area, this condition was not considered hazardous.

B. Collimator

First collimation of the source occurred as the beam passed through the 1/4-in. diameter hole in the 8-in. radius lead cylinder. Another collimator was obtained in the form of an 8 1/4 by 4 by 4-in. lead block with a 3/32-in. diameter hole along the 8 1/4-in. dimension. This collimator was cast with a 3/32-in. diameter steel piano wire rod in it. In order to ensure that the rod could be smoothly withdrawn after casting, it was coated with a commercial preparation called Aquadag which worked very well

for this purpose. The manufacture of the mold and the casting of the collimator was done by the Iowa State University Plumbing Shop.

C. Targets

The single crystal of copper used in the investigation was obtained from the Metallurgy Group at the Ames Laboratory. Since copper is a face centered cubic material, the 111 plane is the most densely packed plane. This plane was located by x-ray analysis utilizing back reflection Laue photography. After the orientation of the 111 plane was determined, the crystal was removed from the x-ray machine and a slug approximately 1/4-in. thick was carefully cut parallel to 111 crystal planes. The cut was made by using a thin carborundum grinding wheel lubricated with large amounts of cold water. The slug was polished using 600 grain emory paper as the final abrasive with cold water as the lubricant. After etching with nitric acid, the slug was returned to x-ray analysis and checked for possible stresses due to cutting and to see if the cut had been made parallel to the 111 plane. The check revealed no apparent stresses due to cutting and that the 111 plane was parallel to the cut face. The single crystal of copper in its finished form was a disc about 1-in. in diameter and 1/4-in. thick with the 111 crystal planes parallel to its circular cross-section.

For comparison purposes in the investigation, a piece of ordinary polycrystalline copper of the same diameter was turned out on a lathe. From this a slug of approximately the desired thickness was cut. With the use of a micrometer and the same techniques of polishing and etching, the

single crystal dimensions were reproduced in the polycrystalline material. A microscopic examination was made of this specimen and the grain diameters were found to be of the order of 20 microns.

D. Target Platform and Mounting

Although the crystal had been carefully cut and aligned, it was necessary to arrange equipment for accurately aligning it when exposed to the gamma-ray beam. For this purpose a U. S. Navy sextant was modified in order that the crystal could be mounted in the position normally occupied by the reflection mirror of the sextant. This arrangement permitted the angular rotation of the crystal to be read in 0.05-min. increments if desired. The crystal mounting was made of plexiglass and the crystal attached with rubber cement.

The support legs of the sextant would not permit free rotation of the detector through the full range desired, so it was necessary to make an additional target holder to which the target could be transferred for measurement of scattered radiation. This was made of two small blocks of wood and attached to one arm of the apparatus on which the detector was mounted as shown in Figure 4. The same crystal mountings were used with both target platforms.

E. Detector

The detector used for the experiment was a model DS-1A scintillation detector manufactured by the Nuclear Instrument and Chemical Corporation.

The sensing element of the detector was a thallium activated sodium iodide crystal. The detector was equipped with a removable lead shield with a 1-in. diameter aperature. To sharpen the field of radiation scanned two lead bricks were placed in front of the instrument leaving a 1/8-in. slit as shown in Figure 4.

F. Detector Platform and Grid

The detector platform was made of laminated plywood in such a manner that the centerline of the detector would lie along the axis of the radiation beam. Stops were provided on the platform in order that the detector could be removed and returned to the platform without changing its relative position on the platform.

In order to measure the angle of rotation of the detector with respect to the crystal, the detector platform was mounted on one arm of a U. S. Navy three-arm navigational plotter with the detector centerline aligned with one of the plotter arms. The three-arm plotter consists of a plastic grid graduated in degrees and two plastic arms whose rotation about the grid center can be measured in one minute increments by means of a vernier on the arms. The plotter is shown in Figure 4.

A hole was bored in the table along the beam axis over which the grid center was mounted. The sextant leg corresponding to the rotation center of the crystal was placed through the grid and into the hole resulting in a firm placement of the crystal directly in the beam and at the center of rotation of the detector.

The combination of detector, detector platform and two lead bricks

proved rather unwieldly for movement of the detector. To alleviate this situation, two boards 1/16-in. thicker than the platform were braced with strap steel and slipped snugly over the detector platform. The two bricks were secured on these boards by strips of wood to provide the 1/8-in. slit in front of the detector. By using some paraffin as lubricant between the boards and the tabletop and removing the detector each time the platform was moved, the combination worked very smoothly.

G. Scaler

A Baird-Atomic model 132 general purpose high speed glow tube scaler was used to provide the high voltage for the scintillation detector and to count the pulses from it. Timing was done by a Baird-Atomic model 960 dual purpose precision timer.

The scaler had a published resolving time of less than five microseconds which was the controlling factor in determining coincidence losses in counting. To determine whether a resolving time of this magnitude resulted in a significant loss in counting rate, use was made of the equation given in Friedlander and Kennedy (4):

$$I^* = \frac{R}{1 - R\tau}$$

where I^* is the rate with no coincidence loss, R is the observed counting rate and τ is the resolving time. For a count rate of 600,000 counts per minute the loss is approximately one percent. For the rates encountered in taking data in this experiment, the losses will be negligible.

Some difficulty was encountered in obtaining consistent readings on the scaler. At times the variation exceeded ten times the statistical deviation based on the 68 percent confidence level. These variations were attributed to fluctuations in the line voltage. Finally, the taking of data during daytime was abandoned in favor of the late evening and early morning hours when the line load could be expected to be more uniform. No difficulty was encountered at these times.

H. Miscellaneous Equipment

Other items of equipment used were a model 5U5A Tracerlab portable survey meter and personnel film badges.

The survey meter was used from time to time to check the radiation level in the working area and to estimate the sharpness and location of the beam of radiation. Personnel film badges were provided by Health Physics from the Ames Laboratory and checked weekly.

V. PROCEDURE

A. Operating Voltage

The scintillation detector was placed in a position to obtain a count rate of approximately 50,000 counts per minute and a curve of count rate versus operating voltage was run. An operating voltage of 1650 volts was selected from the midpoint of the flattest part of the curve.

B. Experimental Geometry

The source was placed in the radiation position and an attempt was made to locate the centerline of the beam without the collimator. Since the counting rate in the beam was too high for the scaler to accomodate, only an approximate location was possible. This did however coincide with what appeared correct from the geometry of the apparatus. The collimator was attached and aligned with the cylinder port by using the 3/32-in. diameter steel rod as an aid. The collimator reduced the counting rate to where it was possible to plot counting rate as a function of detector position and determine the beam centerline. A line was inscribed along the tabletop to mark the location of the beam axis.

The location of the grid, sextant and detector were largely determined by the size of the table, the dimensions of the equipment, and the distance between the beam stop and the lead cylinder. The sextant was mounted at the grid center along the beam axis. Enough room was left

between the collimator and grid center to block off the source by two lead bricks when making adjustments on the sextant or the detector. The detector had to be located in a manner such that the vernier could be read and at the same time leave room for rotation of the detector past the beam stop.

The calculated beam width with the collimator in position was 0.3 degrees. The centerline determination showed a counting peak with a 0.3 degree width at half maximum although there was considerable counting rate at 1.0 degree from the centerline.

C. Reflection Data

Considering the Bragg equation as indicating the conditions for reflection of Cobalt-60 gamma-rays by a single crystal of copper,

$$\sin \theta = \frac{n\lambda}{2d}$$

where for first order reflection; $n = 1$, $\lambda = 9.8338 \times 10^{-3}$ A° and d, the distance between the 111 planes is equal to 2.083 A°,

$$\sin \theta = 0.00236 \qquad \theta \approx 8 \text{ minutes}$$

This meant that the crystal had to be aligned within rather close tolerances to produce reflection of the primary radiation. The sextant appeared adequate for this task.

Measurement of the reflected radiation would require a detector angle

of 2θ or approximately 16 minutes. Unfortunately, even with the degree of collimation obtained, a detector angle of 16 minutes placed the detector too close to the beam of radiation and it was impossible to discern any effects from the crystal. The detector was moved to 1.0 degree where the count rate was approximately 20,000 counts per minute (detector angles are clockwise rotation from the beam centerline about the grid center). Although this angle was too large to obtain reflection from the beam centerline, it appeared reasonable to expect reflection from the outer fringe of the radiation cone. The counting rate of 20,000 counts per minute was desirable from a statistical viewpoint and changes in counting rate could be ascertained more easily.

With the detector fixed at 1.0 degree, the crystal was rotated and one minute counts were plotted as a function of crystal rotation. The results showed a definite peak in the counting rate, so ten-minute counts were taken over the same range in order to reduce the statistical deviation. The data for this run is presented in Table 1 and Figure 5. Since only qualitative results were desired, no correction for background was made and statistical deviation was not considered in plotting the curve.

The single crystal was removed from the sextant and the polycrystalline copper was mounted on the sextant in the same manner. Another run was made over the same range of angles with negative results. The only variations noted were statistical in nature.

From the above it was concluded that some of the gamma-rays were being reflected by the single crystal.

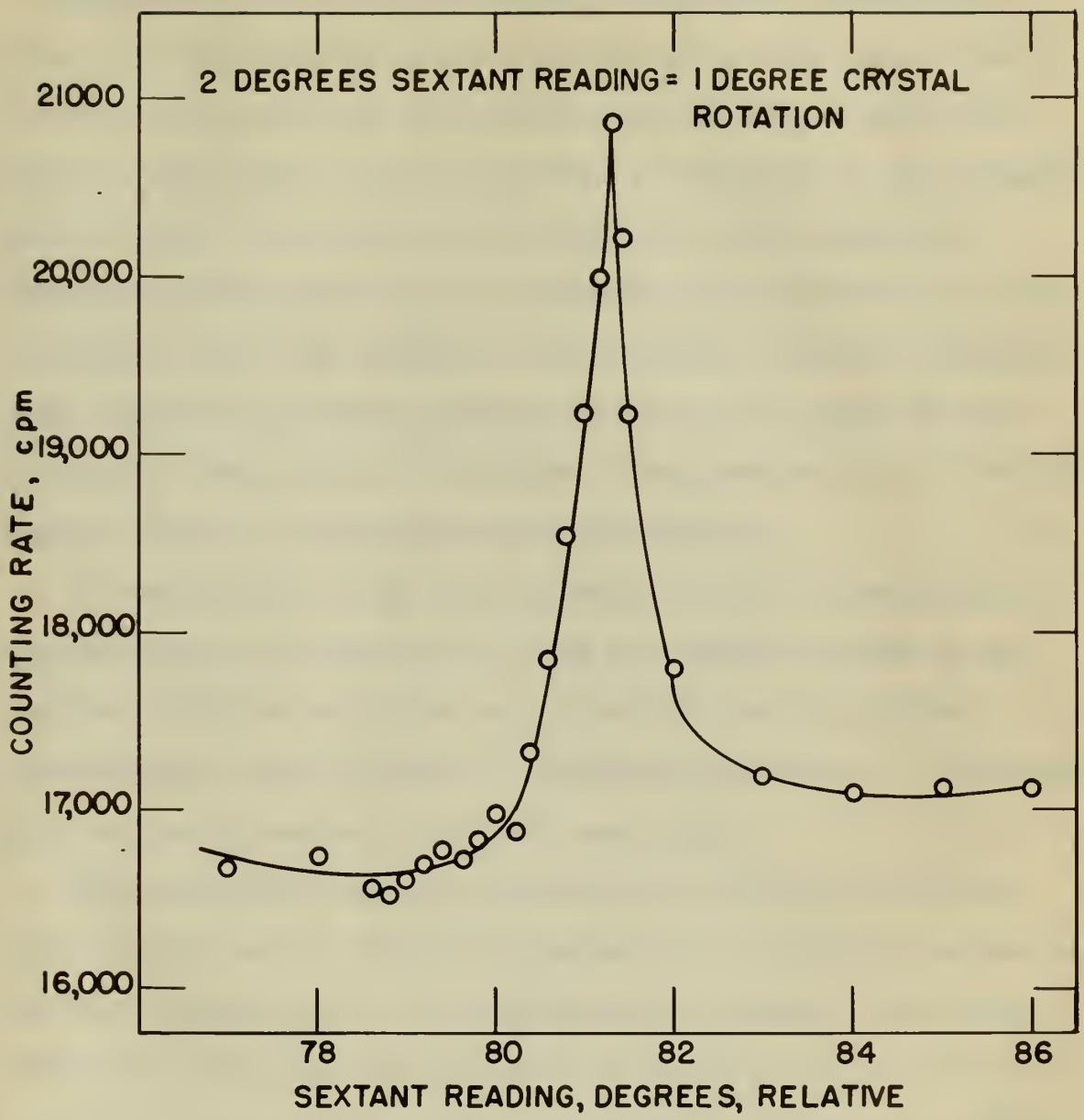

Figure 5. Bragg reflection

D. Scattering Data

Because of the previously discussed difficulty of rotating the detector platform with the sextant in place, the sextant was replaced by the other target platform. The wood platform was aligned and secured where the target would occupy the position corresponding to the reflection peak obtained. The targets remained cemented to their respective plexiglass mountings which could be interchanged on the platform by a pin arrangement. With this equipment, it was possible to take a background count followed by successive readings for the single crystal and the polycrystal without moving the detector. This procedure was used over the range of detector or scattering angles investigated.

In consideration of the time available, only the two extremes of incident angle were selected; i.e., with the reflection planes in the position of observed reflection and perpendicular to this position, respectively. It was felt that the reflection dependency on incident angle would best be illustrated by these two conditions.

The perpendicular case was treated first by rotating the target ninety degrees from the observed reflection peak. Counting rates were so low that counting times of thirty minutes were necessary to obtain any reasonable statistics. The removal, at this time, of the collimator resulted in readings which gave good statistics for ten-minute counting periods. The collimator was not used thereafter in taking the scattering data. Because of geometrical limitations, the maximum scattering angle investigated was one hundred degrees.

5. Implicit Idea

Because of the psychologically disastrous difficulty in relating the derivative directly with the method in class, the problem was replaced by the other target pictures. The word picturing was changed and removed hence the target could exactly the position corresponding to his intellectual ones objective. The targets remained associated to their negative physiological motion could be introduced to the physician by a plan environment. With this explanation, it was possible to have a beginning point defined by environmental evaluation for the single subject and the psychological validity within the behavior. This procedure was used when the image of derivative or evaluating angles increased.

In accomplishing of the time available, only ten were introduced individual angle were evaluated i.e., with the relationship please in the practice of observed inclinations and personalization in this practice, negatively. It was this with the inclination dependence on included angle would have to illustrated to those two conditions.

The psychophysicist came out trained first to imitate the target already depicted from the observed relationship. Consisting values were in two ways measuring times of fairly minutes were increased to obtain the reasonable circumstances. The results, at this time, of the multiplayer measured in knowledge which came given existence for re-observe measuring results. The evaluation was not used technique to taking the practicing data. Because of symmetrical limitations, the evaluations evaluating angle increased was one limited degrees.

After the above run was completed, the crystal was returned to the observed reflection position and readings were taken over the same range of angles with the same procedure.

The scattering data are recorded in Table 2.

VI. RESULTS AND DISCUSSION

The results of this investigation are presented in the form of a plot of counting rate as a function of scattering angle in Figure 6.

No particular significance is attached to the difference in magnitude of the scattered radiation for the two different positions of the same material. This difference may be attributed, however, to the difference in the actual amount of material exposed to the radiation in the two positions. The small dip in the curve for the perpendicular case at about ninety degrees may be attributed to the fact that there was a significant increase in material between the detector and the scattering elements as the detector was rotated past the long dimension of the target.

The objective of this study was to determine a possible use of single crystals as a shielding material. Since the interaction of Cobalt-60 photons with copper is primarily by Compton effect, it was postulated that the effectiveness of a single crystal as a shielding material could be ascertained from a comparison of scattering by a single crystal and a polycrystalline slug of the same dimensions. It was also assumed that scattering (reflection) by a single crystal would be a function of the incidence angle, i.e., the angle between the incident radiation and the reflecting planes. The latter assumption led to the investigation of the two incidence angles separately.

Reference to Figure 6 will show that there is a small difference in the scattering exhibited by the two materials. There does appear to be a trend around the ninety degree position in both cases. That this is

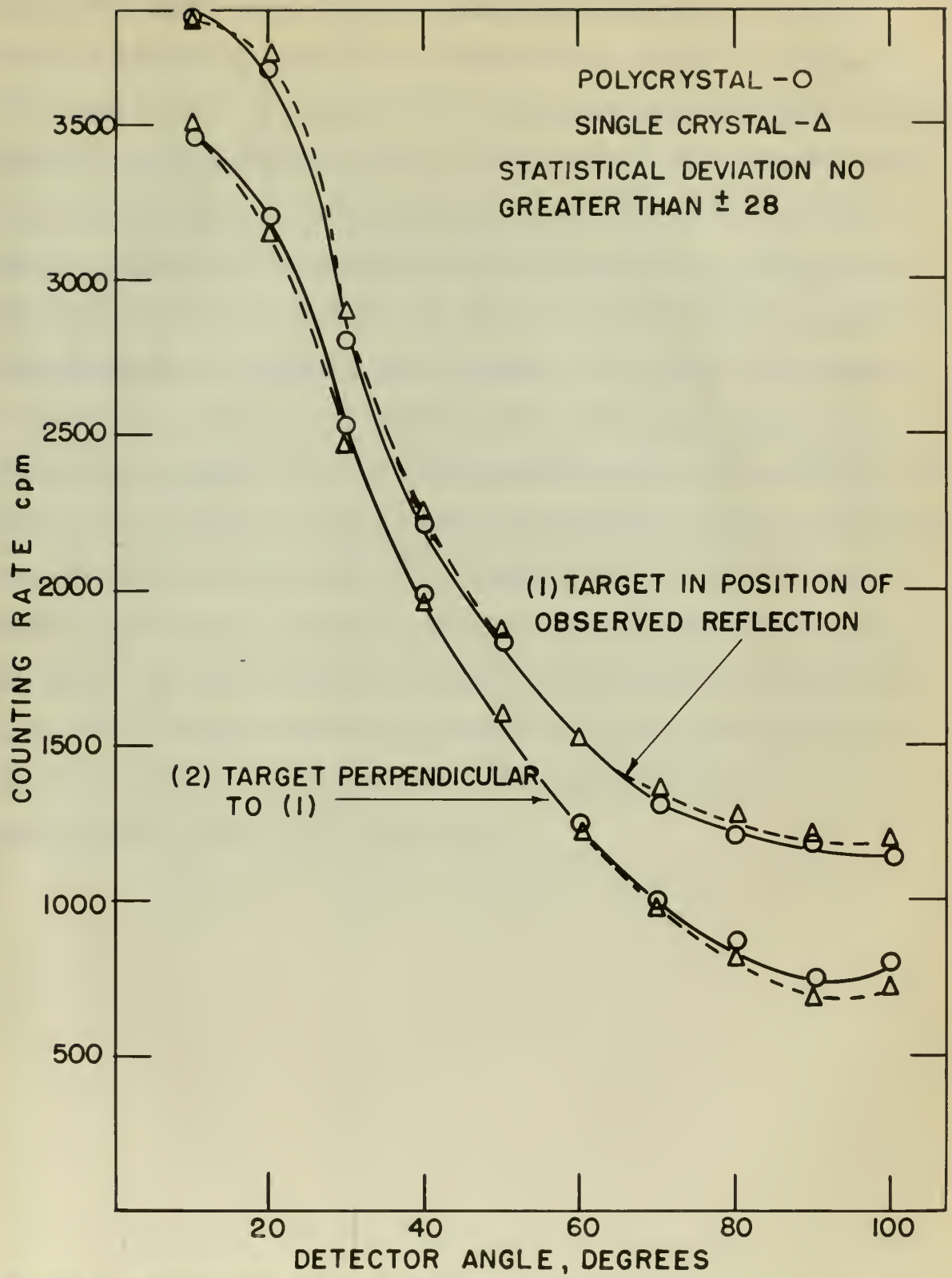

Figure 6. Scattering comparison

significant is not known. The geometry of the experimental equipment prevented measurement past the one hundred degree position. Of the two cases considered, that corresponding to the position of previously observed reflection consistently gave higher readings for the single crystal while the perpendicular case consistently gave lower readings for the single crystal. Although the differences are small, they give an indication of the scattering effectiveness as a function of incidence angle. It appears that increasing the incidence angle decreased the crystal effectiveness as a scatterer. In fact, the single crystal was less effective in the perpendicular position than the polycrystalline copper. Those photons that were scattered at angles corresponding to the critical angle for reflection were partially reflected. The reflection away from the beam centerline when the crystal was aligned for reflection was manifested in the small increase in scattered radiation over the scattering angles investigated. It is noted also that those photons scattered in the vicinity of ninety degrees were partially reflected when the crystal planes were perpendicular to the beam of radiation.

VII. CONCLUSIONS

The results of this experiment indicate that there is a small change in scattering characteristics of copper in its single crystal form. Its scattering effectiveness is a function of the angle of incidence of the radiation on the reflecting planes. The scattered radiation within the crystal appears to be reflected in a manner similar to that which the incident radiation undergoes.

From a practical viewpoint there seems to be little to indicate the use of single crystal copper as a shielding material. Even if the additional cost and difficulty of fabrication are not considered, the advantages appear too small to be beneficial.

VIII. RECOMMENDATIONS

The combination of scattering and reflection within a single crystal appears worthy of further study. Since the mechanism by which it occurs is complex, a theoretical analysis is suggested prior to further experimentation. Perhaps the method of random sampling (Monte Carlo) could be used as it has been in solving gamma-ray attenuation problems (5, p. 183). It would amount to adding the random sampling of reflection probability to probabilities of collision, absorption and scattering already present. The procedure would be long and tedious and would require the use of high speed computers.

In this investigation, no attempt was made to measure the energy spectrum of the reflected or scattered radiation. The use of a recording spectrometer would have been helpful in interpreting the results, and a positive identification of the reflected radiation would have been possible. It is recommended that a spectrometer be used in conjunction with a scaler in any further work of this type.

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XI. APPENDIX

Table 1. Experimental data for reflection

Detector angle: one degree

Counting time: ten minutes

Sextant angle (degrees)	Counting rate (cpm)	Sextant angle (degrees)	Counting rate (cpm)
77.0	16692	80.6	17820
78.0	16741	80.8	18530
78.6	16578	81.0	19243
78.8	16529	81.2	19994
79.0	16639	81.3	20860
79.2	16698	81.4	20203
79.4	16765	81.5	19224
79.6	16731	82.0	17801
79.8	16814	83.0	17197
80.0	16970	84.0	17112
80.2	16854	85.0	17168
80.4	17330	86.0	17115

Table 2. Experimental data for scattering

No collimator

Counting time: ten minutes

Detector angle (degrees)	Background (cpm)	Poly-crystal (cpm)	Poly-crystal net (cpm)	Single crystal (cpm)	Single crystal net (cpm)
(1) 111 crystal planes in position of observed reflection					
10	1546.2	5403.6	3857 ± 26	5391.8	3845 ± 26
20	501.2	4184.4	3683 ± 21	4228.2	3727 ± 21
30	340.0	3159.8	2820 ± 19	3241.0	2901 ± 20
40	411.8	2627.8	2216 ± 17	2647.2	2232 ± 16
50	411.4	2244.6	1833 ± 15	2269.2	1858 ± 15
60	404.0	1925.2	1525 ± 15	1924.8	1521 ± 15
70	380.2	1699.8	1320 ± 15	1730.4	1350 ± 15
80	378.4	1601.2	1223 ± 14	1644.0	1266 ± 14
90	372.6	1557.0	1184 ± 14	1570.8	1198 ± 14
100	398.2	1539.4	1141 ± 13	1583.4	1185 ± 13
(2) 111 crystal planes perpendicular to (1)					
10	2200	5670	3470 ± 28	5681	3481 ± 28
20	639	3838	3191 ± 21	3799	3160 ± 21
30	379	2888	2509 ± 18	2857	2487 ± 18
40	350	2316	1966 ± 16	2313	1963 ± 16
50	391	1978	1587 ± 15	1978	1587 ± 15

Table 2. (Continued)

No collimator

Counting time: ten minutes

Detector angle (degrees)	Background (cpm)	Poly-crystal (cpm)	Poly-crystal net (cpm)	Single crystal (cpm)	Single crystal net (cpm)
60	398	1635	1237 ± 14	1617	1219 ± 14
70	387	1353	966 ± 13	1364	977 ± 13
80	373	1215	842 ± 13	1190	817 ± 13
90	382	1116	734 ± 12	1070	688 ± 12
100	409	1190	781 ± 13	1132	723 ± 13

Sample Calculations

Standard deviation for scattering data. (Table 2, line 1.)

$$\sigma_t = \frac{(\text{total count})^{\frac{1}{2}}}{\text{counting time}} = \frac{(54036)^{\frac{1}{2}}}{10} = 23.2$$

$$\sigma_{bg} = \frac{(\text{background count})^{\frac{1}{2}}}{\text{counting time}} = \frac{(15462)^{\frac{1}{2}}}{10} = 12.5$$

$$\sigma_{net} = (\sigma_t^2 + \sigma_{bg}^2)^{\frac{1}{2}} = 26.$$

Critical angle for reflection. (p. 25)

$$\sin \theta = \frac{n\lambda}{2d}$$

$$n = 1$$

$$\lambda = \frac{hc}{E} = \frac{6.625 \times 10^{-27}\text{erg-sec} \times 2.9776 \times 10^{10}\text{cm/sec}}{1.602 \times 10^{-6}\text{erg/mev} \times 1.252 \text{ mev} \times 10^{-8}\text{cm/A}^\circ}$$

$$\lambda = 9.8338 \times 10^{-3} \text{ A}^\circ$$

$$d = 2.083 \text{ A}^\circ$$

$$\sin \theta = 0.00236$$

$$\theta \approx 8 \text{ minutes.}$$

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